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Neck Muscle Fatigue Resulting from Prolonged Wear of Weighted Helmets

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Air Force Research Laboratory
Human Effectiveness Directorate
Biosciences and Protection Division
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14. ABSTRACT

Today's flight helmet incorporates targeting and cueing systems enabling the pilot to accurately cue onboard weapons against enemy aircraft while performing high-G aircraft maneuvers. While these systems undoubtedly increase a pilot's capabilities, one obvious drawback to putting all this equipment on the pilot's helmet is the increase in helmet weight that shifts the combined head and helmet center of gravity (CG) forward, while increasing moments of inertia on the neck. Operational concerns associated with the heavier helmet may result in decreased performance from muscle fatigue and increase in neck injury during ejection. The objective of this study was to measure the human's level of neck and upper torso fatigue while wearing United States Air Force helmets of varied mass properties (weight, CG, moments of inertia) for durations up to 8-hours. Results found that helmets with a forward CG shift were significantly more uncomfortable on the subject's neck and back than the helmets with a normal CG shift. Significant increases in upper neck and upper and lower back discomfort were reported as early as hour 2 and continued throughout the 8-hour session. The 4.5 lb helmet with forward CG shift was significantly more uncomfortable on the subjects than the 6.0 lb helmet with nominal CG shift.

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SUMMARY

Current U.S. Department of Defense (DoD) helmet systems, such as the Joint Helmet Mounted Cueing System (JHMCS), JHMCS Night Vision Cueing and Display (NVCD), and the Joint Strike Fighter Helmet Mounted Display System (JSF HMDS) incorporate targeting and cueing systems into the helmet enabling first look, first shot, high off-boresight weapons engagement. This capability enables the pilot to accurately cue onboard weapons against enemy aircraft while performing high-G aircraft maneuvers. These systems also feature advanced head tracking capabilities with near-zero latency in order to provide a virtual heads-up display and imagery screen anywhere the pilot's head moves. Critical information and symbology such as targeting cues and aircraft performance parameters are graphically displayed directly on the pilot's visor rather than on a forward mounted Heads-Up Display (HUD) as used in legacy aircraft. The JSF HMDS and the JHMCS NVCD are also capable of incorporating Night Vision Devices (NVD) providing night imagery that applies to both air and ground attacks.

While these systems undoubtedly increase a pilot's capabilities, one obvious drawback to putting all this equipment on the pilot's helmet is the increase in helmet weight that shifts the combined head and helmet center of gravity (CG) forward, while increasing the moments of inertia on the neck. Some of the operational concerns associated with the use of a heavier, and possibly unbalanced system include upper torso, head, and neck muscle fatigue that may result in decreased performance, and the possibility of increasing neck injury risk during egress (ejection), especially the longer the helmet system is worn. These concerns are realistic and need to be considered due to prolonged helmet wear during long missions, and the expanded pilot population that now includes small females.

INTRODUCTION

Unites States Navy, United States Air Force, and European Air Force surveys in the 1980s documented neck injury rates of 50% or higher ranging from minor neck strain to cervical vertebral fracture[3,11-14,17]. Lighter helmets were developed and implemented in hopes of reducing injuries, but the current trend has been to mount critical information and symbology on the helmet. The new generation of HMDs, and NVDs will likely enable pilots to improve their effectiveness to complete their mission. However, the integration of these systems has resulted in increased helmet weight, an alteration of the head and helmet CG, and greater torque on the neck. These changes may lead to greater neck fatigue and susceptibility to neck injury. There may be an increase in cervical loads during aircraft ejections (catapult, windblast, parachute opening shock), an increase in acute and chronic pain or injury from fatigue associated with prolonged wear (vibration, sustained acceleration), and compromised effectiveness for long missions.

The neck load limits (flexion, extension, and rotation) under operational conditions are unknown. Some studies suggest that most in-flight neck injuries occur when pilots move their heads while pulling Gs or when an unsuspecting "back-seater" is subjected to a high-G maneuver[2-3,10,17,31].

A study investigating the head and neck movements in F-16 cockpits predicted that the forces generated in the trapezius and sternocleidomastoid muscles during accelerations ranging from 5-7 +Gz nearly reached their strength capacity[15].

Tests conducted by the Biomechanics Branch of the 711th Human Performance Wing (711 HPW/RHPA) evaluated the effects of variable helmet mass properties on the biodynamic response of male and female human volunteers exposed to vertical (+Gz) accelerations using the vertical deceleration tower[4,9,18,20-23]. A similar study investigated the effects of varied helmet mass properties on human response during lateral +Gy Impact on a horizontal impulse accelerator[24]. A continuation of this research was recently conducted evaluating helmet mass property effects during frontal impacts (-Gx)[8]. Another recent study explored the effects of varied helmet weight on human neck response during retraction using the Body Positioning and Restraint Device (BPRD) [29]. Researchers have also looked at how neck strength and endurance may be correlated to neck pain and injury[14]. One may assume that a stronger, well-exercised neck would result in less pain, and injury, but data supporting this is inconsistent[3,11-12].

Another issue is that one's neck strength, tested isometrically, may not correlate with their ability to endure dynamic exertions greater than 70% of their maximum. For these muscles, factors such as the ability to supply the tissue with ample oxygen and rid it of the waste products such as lactic acids, rather than one's maximum strength, determine endurance[19]. These findings suggest that a more meaningful approach addressing how neck strength and endurance may be correlated to neck pain and injury, may be to investigate these correlations in a dynamic environment.

Electromyography (EMG) has been widely used to investigate muscle fatigue. EMG has become an increasingly popular and useful tool used to quantify muscle strength and fatigue. Typically, a muscle group is isolated, and monitored for strength and fatigue by measuring relative changes in EMG root mean square amplitudes and decreases in EMG frequency content. With surface EMG, fatigue is generally accompanied by increases in amplitude[7,26] and shifts in the EMG spectrum to lower frequencies during prolonged contractions[5,6,16,26,30,34]. Amplitude is a function of both the number of motor units recruited and the frequency of their discharge. The frequency components of EMG are a function of the duration of motor units' action potentials, the geometry of the surface electrodes, the degree of motor unit synchronization, and the conduction velocity of action potentials on the sarcolemma[25]. Well prescribed methods exist for the use of EMG to quantify fatigue, but their efficacy in dynamic environments is uncertain[10].

In 1983, Phillips and Petrofsky measured Maximum Voluntary Contractions (MVCs) of the upper trapezius and sternocleidomastoid using a fixture called the isometric head dynamometer[27]. Subjects were fitted with flight helmets of various NVG configurations and asked to perform neck rotations for up to 35 minutes. The goal of this study was to quantify the fatigue of neck muscles when loaded by weighted flight helmets. Another study by Phillips and Petrofsky evaluated neck muscle fatigue using different helmet weights and CGs[28]. A helmet simulator was used to simulate helmet weights up to 9.0 lbs with 5 different CG locations. Neck muscle fatigue was measured by isometric endurance time.

The Naval Air Warfare Center (NAWC) in 2001 reported an investigation of the dynamic strength capabilities of small-stature female pilots in performing tasks such as aerial combat maneuvers and failure modes. The tasks were performed under simulated flight conditions in a dynamic flight simulator. A typical day's testing consisted of a sequence of turns lasting about 45 minutes. The major concern was whether the small females had sufficient upper body and neck strength, and endurance to perform the duties. The study showed that the four small

subjects tested were able to demonstrate sufficient strength and endurance to safely fly physically strenuous missions. However the subject sample was small and the authors felt that a larger subject sample was necessary to increase the statistical power of the results[33]. A second study by NAWC, also published in 2001, investigated the dynamic strength capabilities needed to exert the required ejection seat actuation pull force under various conditions including typical flight conditions while wearing helmets with added weight. In this study, six small females were able to meet the minimum pull forces required to eject. However, some difficulties were noted with tasks affected by reach, fit, and accommodation issues. Again, the small subject sample size makes it difficult to generalize the results to a larger population[32].

The objective of the current USAF study was to measure the human subjects' level of neck and upper torso fatigue while wearing helmets of varied mass properties (weight, CG, moments of inertia) for durations up to 8-hours. Upper torso and neck muscle fatigue were quantified by measuring muscle activity, strength, endurance, discomfort, and performance while wearing five helmets with different weights, and mass distributions for up to 8-hours. The results are being used to provide information regarding the safety and performance of helmet mounted systems during long missions. The results also provide a baseline for future model development that seeks to simulate a living human with active muscles, thus providing greater utility to modeling and simulations in the future.

METHODS

Human volunteer's neck and upper torso strength, endurance, muscle activity, subjective comfort level, and visual search task performance were measured or recorded while wearing one of five helmet configurations per session. During each session, the subject was seated in an F-15 ACES II ejection seat with a 17° recline, with each session lasting a maximum of eight hours. During each session, the subjects were required to pull on a neck strength device (NSD) to measure muscle strength and endurance while being monitored with an electromyography (EMG) system, answer a subjective comfort survey, complete a visual search task, and perform a flight routine/awareness check. A 48 hour rest period was mandatory between test sessions. Below is a list of the test procedures followed for each test session.

a) Test conductor will inform the subject about that particular session's equipment and procedures.
b) Subject will complete pre-test comfort questionnaire.
c) Subject will be fitted with 6 EMG sensors and 1 reference electrode.
d) Subject will be fitted with (don) the helmet of the day.
e) Subject will perform pre-test neck MVCs in extension in the NSD three times with approximately 45-60 seconds between MVCs, and EMG will be collected and saved. The peak for those 3 trials will be recorded as the 100% pre-test MVC. The 70% MVC will be calculated at this time.
f) Subject is seated in an ACES II seat and will watch a movie, read, or similar until asked to perform the Flight Routine/Awareness Check (every 15 minutes).
g) During the Flight Routine/Awareness Check subject will look at the designated target for 10 seconds, and then be asked to look at the next target, and so forth.
h) The subject will complete the visual search task at the end of the odd hours, just prior to performing that hour's 70% MVC.

i) After the search task is completed, the subject will get up from the ACESII seat and perform the 70% MVC, for as long as he/she can stay within the 70% ± 2 lb. range on the NSD. EMG will be collected and saved.
j) On the even hours, the subject will complete a comfort survey on returning to the ACESII seat just following the 70% MVC.
k) Steps f-j will be repeated six more times.
l) Upon completion of the 7th hour, the subject will perform the last 70% MVC, fill out the final comfort questionnaire, and perform the post-test 100% MVC (3 trials). EMG will be collected and saved.
m) The subject will remove the helmet, the test conductor will remove the EMG leads, and ask if the subject has any medical related comments and if they'd like to talk to a medical monitor, and remind them to perform their cool down exercises.
n) The subject is paid for that day's session.

In addition to the steps detailed above, it is important to note the subjects were permitted to use the rest room as needed. Subjects were encouraged to perform leg stretching and isometric exercises as often as needed to maintain proper circulation and help minimize discomfort. Subjects could terminate the session at their own discretion at any time.

Subjects

A total of 25 volunteer subjects, 14 male and 11 female, participated in this study. Before acceptance into the study, the subjects filled out a medical prescreen questionnaire to exclude any subjects that had pre-existing risk factors. Each subject was reviewed and approved by the medical monitor. The subjects wore casual civilian clothing during testing and were compensated after each session for their participation. An attempt was made to include an equivalent number of male and female subjects. Anthropometric measurements were collected from each subject prior to testing (Table 1). The test program was reviewed and approved by the Wright-Site Institutional Review Board and all subjects provided informed consent to participate prior to any testing (Protocol F-WR-2005-0023-H).

Table 1. Subject Anthropometry

	Males			**Females**			**Group**	
	Range	**Mean**	**SD**	**Range**	**Mean**	**SD**	**Mean**	**SD**
Age (yrs)	18-55	26.9	9.4	18-38	23.0	6.2	25.2	8.2
Weight (lbs)	115.0-301.0	184.7	47.9	115.5-196.0	146.0	23.8	167.7	43.2
Height (cm)	167.6-191.5	177.1	6.4	151.0-186.0	163.4	9.3	171.1	10.3
BMI	18.6-39.2	26.5	5.6	19.9-29.6	24.7	2.9	25.7	4.6
Sitting Height (cm)	86.2-98.6	91.5	3.8	82.6-94.4	87.0	3.6	89.6	4.3
Neck Length - Occiput to T1 (cm)	11.1-17.7	14.5	1.9	9.3-16.4	13.4	2.1	14.0	2.0
Face Length (cm)	10.9-13.4	12.2	0.7	10.5-12.5	11.4	0.6	11.9	0.8
Face Breadth (cm)	13.1-15.7	14.3	0.6	12.4-14.1	13.2	0.5	13.9	0.8
Head Length (cm)	18.6-20.7	19.8	0.5	18.3-20.1	19.0	0.5	19.5	0.7

Head Breadth (cm)	14.5-16.2	15.3	0.4	13.6-15.3	14.6	0.4	15.0	0.6
Head Circumference (cm)	54.5-58.9	56.8	1.5	53.1-57.4	55.5	1.4	56.3	1.6
Neck Circumference at Mid-Cervical Spine (cm)	33.6-46.5	39.3	3.7	29.1-35.2	32.4	1.9	36.3	4.7
Neck Base Circumference Including Trapezius Musculature (cm)	40.1-52.1	44.4	3.7	34.8-43.2	38.3	2.1	41.7	4.4
Neck Base Circumference – CAESAR Method (cm)	40.7-56.0	47.1	3.8	40.8-49.0	43.9	2.4	45.7	3.6

Helmets

Three sizes (M, L, XL) of the HGU-55/P flight helmet were modified to simulate either a currently operational or "in-development" helmet mounted system. The helmets were modified with a telescoping set of "halo" type rings that allowed for weights to be placed anywhere along the rings including on the sides of the helmet (adjacent to the earcups). Five different helmet configurations were ballasted to match target helmet systems (Table 2). The testing sequence was counterbalanced (Latin Square design) so that subjects would proceed through the configurations from Cell A to Cell E, but the starting cell letter was different for different subjects. The weights of the helmets were 3.0, 4.5, or 6.0 lbs. The 3.0 lb. helmet was ballasted to match the weight and CG of the HGU-55/P helmet with a MBU-20/P oxygen mask. The 4.5 lb. helmet was ballasted to match the approximate weight and CG of the HGU-55/P helmet with MBU-20/P oxygen mask, plus a set of NVGs such as the ANVIS-9. The 6.0 lb. helmet was ballasted to match the approximate weight and CG of the HGU-55/P helmet with MBU-20/P oxygen mask, plus a heavier set of NVGs such as the PNVG (Panoramic Night Vision Goggle) or NVCD system. In addition to these large forward CG shift configurations, the 4.5 lb. and 6.0 lb. helmets were also configured with a nominal CG shift by putting the weights on the sides of the helmet. The 6.0 configurations were approximately 0.5 lb. heavier than the actual weight of the target helmets, but were chosen to serve as a "worse-case" weight scenario. The target helmet data were known because the helmet systems had been measured prior to this study using proven equipment and methods[1]. Examples of nominal CG shift and forward CG shift configurations are shown in Figure 1. The helmets were measured on a Large ADAM manikin head with known mass properties to determine the existing head CG shift when the helmet of interest was worn. The helmets' mass properties data along with the manikin head data are listed in Table 3. The CG data was recorded with respect to the manikin head's anatomical coordinate system (Frankfort plane), and with respect to the manikin's head/neck joint (Figure 2).

In December 1991, an internal USAF consultation report entitled "Interim Head/Neck Criterion" was prepared by AFRL/RHPA to address the issue of ejection safety in helmet worn mass[18]. A plot showing recommended limits of helmet weight and weight distribution (CG) for the x-axis (longitudinal) and z-axis (vertical) was developed and referred to as the "Knox Box." The limits were based on the entire head supported weight (helmet + mask), as measured with the Large ADAM manikin head. The CG criteria are with respect to the manikin head's anatomical coordinate system. Although this criteria was developed to allow a safe ejection with helmet mounted systems, the helmet weight limits also considered helmet effects on pilot fatigue and performance. The criteria were created for the B-52 seat and the ACES II seat based on nominal

acceleration during the catapult phase of the ejection sequence. Helmet weight limits of 4.0 lb. for the B-52 seat, and 5.0 lb. for the ACES II were established. Helmet CG limits are -0.8 to 0.5 in. for the x-axis, and 0.5 to 1.5 in. for the z-axis. Figure 3 shows the helmets used in this study plotted with respect to the Knox Box criteria (red dashed line). Only the 6.0 lb. helmets used in this study were outside the recommended limits for weight and CG.

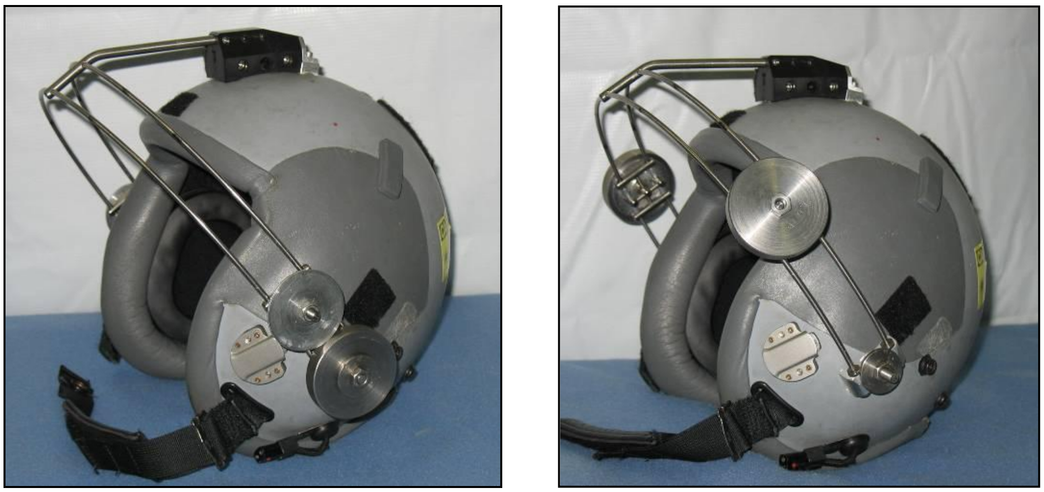

Figure 1. Nominal CG Shift (left), Forward CG Shift (right)

Table 2. Helmet Configurations

Cell	Helmet Weight	Head/Helmet CG Shift
A	3.0 lb.	Baseline
B	4.5 lb.	Nominal
C	4.5 lb.	Forward
D	6.0 lb.	Nominal
E	6.0 lb.	Forward

Table 3. Helmet Mass Properties

Helmet CG Data WRT Head Anatomical Axes System

Configuration	**(cm)**			**(in.)**		
	X	**Y**	**Z**	**X**	**Y**	**Z**
Cell A: 3 lb.	-0.46	0.00	2.77	-0.18	0.00	1.09
Cell B: 4.5 lb.	-1.17	0.00	2.41	-0.46	0.00	0.95
Cell C: 4.5 lb. forward CG	0.48	0.00	2.82	0.19	0.00	1.11
Cell D: 6.0 lb.	-1.27	0.00	2.16	-0.50	0.00	0.85
Cell E: 6.0 lb. forward CG	1.47	0.00	2.87	0.58	0.00	1.13
ADAM manikin head	-1.40	0.25	2.51	-0.55	0.10	0.99

Helmet CG Data WRT Head/Neck Joint Axes System

Configuration	**(cm)**			**(in.)**		
	X	**Y**	**Z**	**X**	**Y**	**Z**
Cell A: 3 lb.	1.37	0.00	5.00	0.54	0.00	1.97
Cell B: 4.5 lb.	0.74	0.00	4.55	0.29	0.00	1.79
Cell C: 4.5 lb. forward CG	2.29	0.00	5.23	0.90	0.00	2.06
Cell D: 6.0 lb.	0.64	0.41	4.29	0.25	0.16	1.69
Cell E: 6.0 lb. forward CG	3.25	0.00	5.46	1.28	0.00	2.15
ADAM manikin head	-1.40	0.25	2.51	-0.55	0.10	0.99

Principal Moments of Inertia

Configuration	(kg-cm^2)			(lb.-in.^{2})		
	X	Y	Z	X	Y	Z
Cell A: 3 lb.	399.22	371.08	349.67	136.42	126.81	119.49
Cell B: 4.5 lb.	549.89	350.05	488.63	187.91	119.62	166.97
Cell C: 4.5 lb. forward CG	557.11	419.4	491.13	190.38	143.32	167.83
Cell D: 6.0 lb.	672.13	345.13	613.52	229.68	117.94	209.65
Cell E: 6.0 lb. forward CG	635.54	472.29	733.18	217.18	161.39	250.54
ADAM manikin head	351.29	546.87	484.48	120.04	186.88	165.56

Weights

Configuration	(kg)	(lb.)
Cell A: 3 lb.	5.61	12.35
Cell B: 4.5 lb.	6.29	13.84
Cell C: 4.5 lb. forward CG	6.29	13.84
Cell D: 6.0 lb.	6.97	15.34
Cell E: 6.0 lb. forward CG	6.97	15.34
ADAM manikin head	4.25	9.34

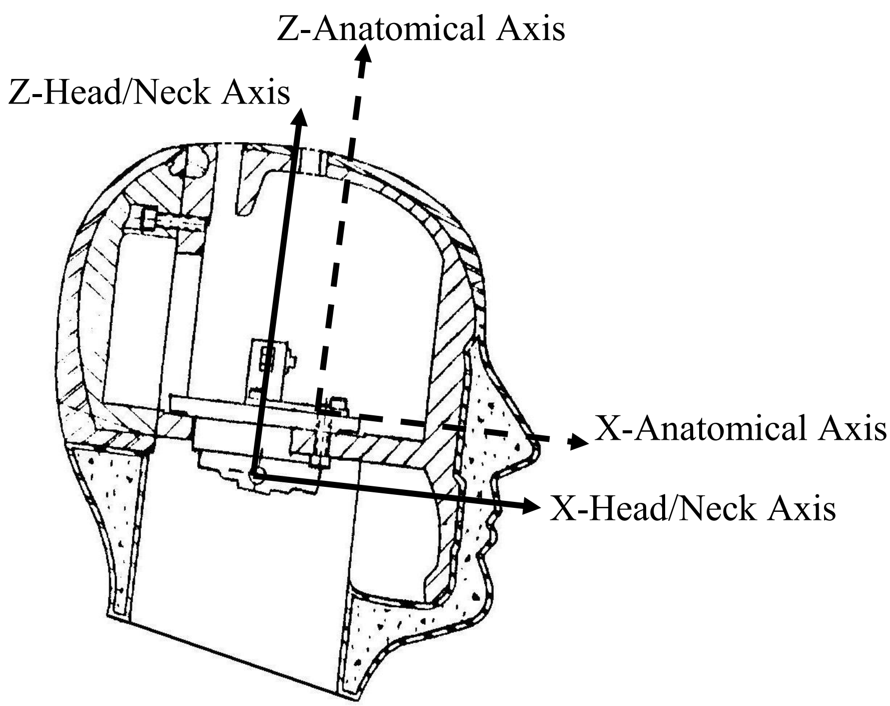

Figure 2. Manikin Head CG Axes Systems

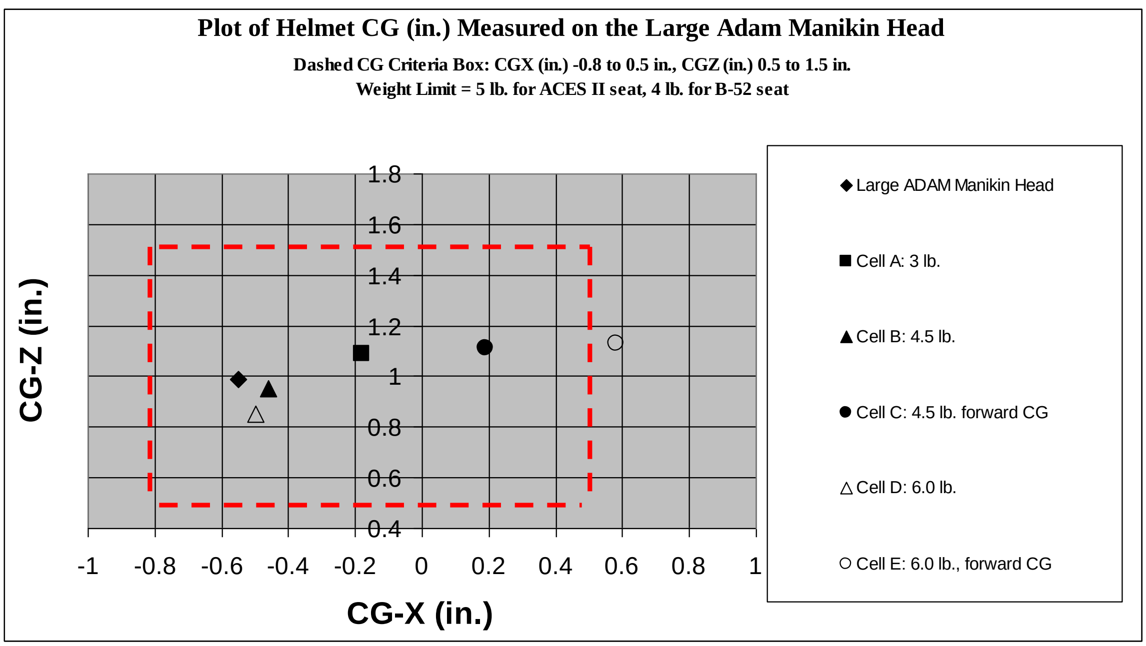

Figure 3. Helmets Plotted with respect to the Knox Box Criteria (dashed line)

Neck Strength Device

The neck strength device (dynamometer) used to measure the subjects' neck strength (100% MVC) and endurance (70% of MVC) consisted of an adjustable chair and adjustable load cell (Figure 4). The subject was seated in a manner to minimize any "cheating" and isolate the intended muscles. The subjects' lower legs and feet were placed on an extended foot rest so they could not be used to push, and their arms were hung at their sides so they could not brace. Likewise, a lap belt was not used in an attempt to minimize bracing and to concentrate on using the neck and upper torso muscles only. The seat back was adjusted so it was either at the level with, or just above the top of the shoulders. The subject's helmet (front of the halo device) was attached to an adjustable strap that attached to the load cell. The load cell was adjusted so the strap was either level or slightly elevated at the load cell when pulled taunt. This was done to ensure the helmet did not rotate down on the subject's forehead and nose when pulling. The adjustment of the strap length also ensured that the subject's cervical spine was vertical prior to starting the measurements. The load cell measured the force when the subject pulled on the strap in a rearward direction (neck extension). Visual and auditory feedbacks were provided while the subject pulled. For the strength (100% MVC) pulls, a computer monitor displayed the real-time force plot from the load cell. For the endurance (70% of MVC) pulls, the target force range (70% ± 2 lb.) was displayed on the monitor and a voice command was provided. The monitor displayed three horizontal lines with the middle line representing the target, the top line as the upper extreme, and the bottom line as the lower extreme (Figure 5). The voice command instructed the subject to either pull "harder" or "easy" if the subject was not able to stay in the targeted range.

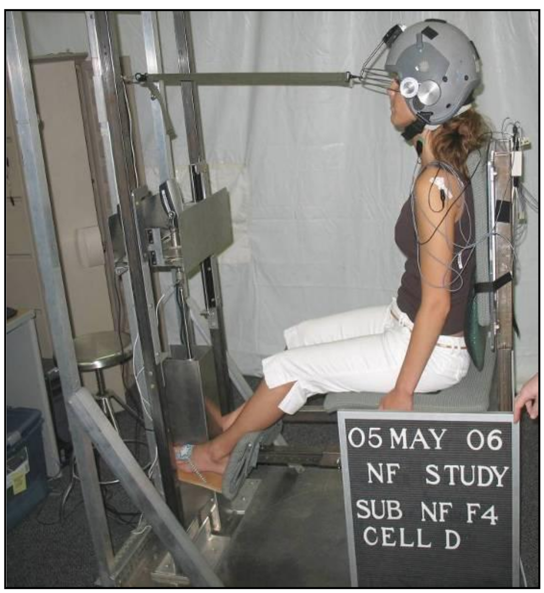

Figure 4. Subject Using the Neck Strength Device

Three 100% MVCs were collected at both the beginning and the end of the test session to measure the subject's neck strength. The subject was instructed to pull as hard as he or she could for a length of no more than 4 seconds with one minute of rest-time in between each MVC. The highest of the three MVCs was considered the actual MVC. The neck endurance target was then 70% of the MVC. The endurance runs were conducted at the end of each hour following the

MVCs. The subject was instructed to hold 70% +/- 2 lb. for as long as they could or for a maximum of three minutes. If at any time the test conductor felt the subject was not consistently able to stay within the range, the endurance pull was stopped. The subject could also stop pulling at any time if it became too difficult or painful.

Figure 5. Visual Feedback Screen for Endurance Testing

Electromyography

Surface electromyography (EMG) was used to quantify the target muscles' level of fatigue. EMG was collected from the left and right pairs of the upper trapezius muscle at the level of the splenius capitus (SC), upper trapezius (UT) at the base of the neck, and sternocleidomastoid (SCM) muscles (Figure 6). All test conductors were trained as a group on the use and placement of the sensors to assure consistent placement of the sensors on the target from session to session, and regardless of test conductor. The subjects' skin was prepped with an abrasive gel and then cleaned with alcohol swabs prior to electrode placement. An adhesive spray and double sided tape were used to affix the sensors to the skin. The sensors were placed perpendicular to the muscle fibers at the beginning of the test session and remained in place for the duration of the session. If needed, medical tape was used on the back of the sensor to hold it in place. A reference sensor was placed on the left acromion process (lateral side of shoulder), or on the left olecranon (posterior side of elbow). Muscle activity was monitored and recorded during the strength and endurance tests using a Delsys Bagnoli-8 EMG system. All data were analyzed using the DelSys® EMG Works Analysis 3.5 Program.

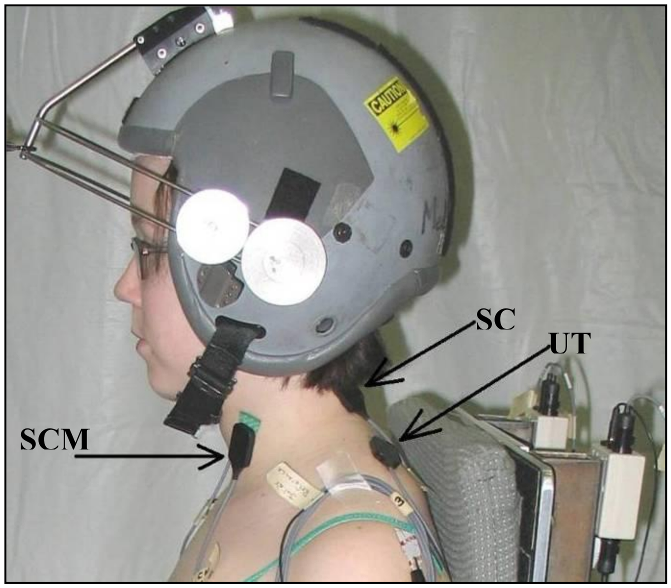

Figure 6. EMG Placement on Subject

Subjective Comfort Survey

A comfort survey was used to determine if a correlation existed between helmet configuration and perceived comfort and fatigue. The subjective comfort survey was completed every even hour (hours 2, 4, 6, 8) throughout the test session as well as pre and post-session. A 7-point Likert scale was used. The subjects rated their comfort level for six different body regions: head, upper neck, lower neck, shoulders, upper back, and lower back. The subjects remained seated while taking the comfort survey. The survey was displayed on a 19" computer monitor. An example of the survey is shown in Figure 7. A mouse was used to select the perceived comfort level.

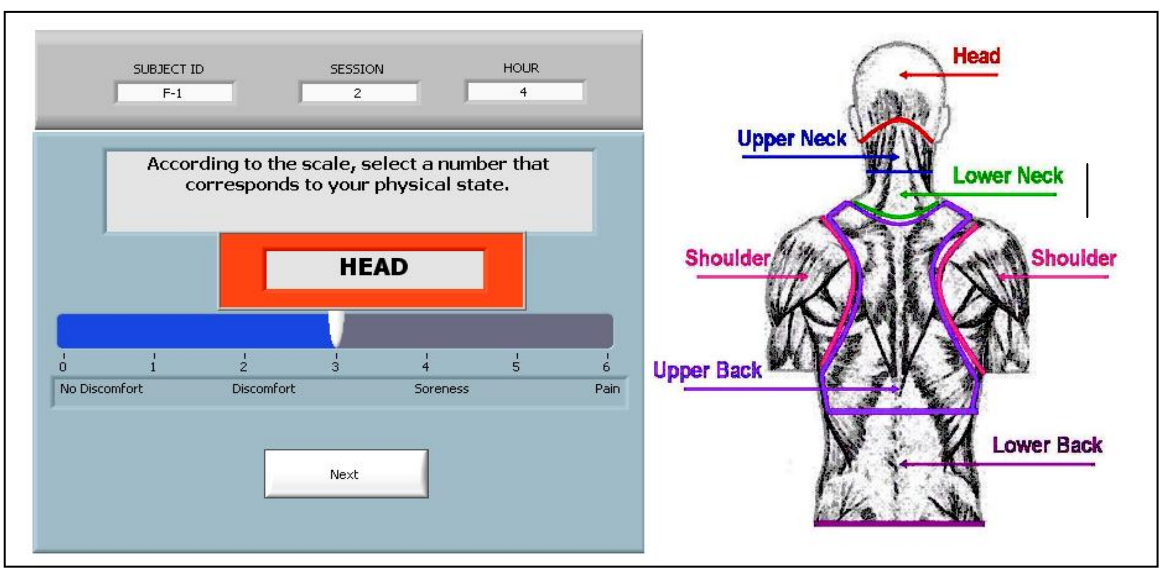

Figure 7. Example of Subjective Comfort Survey

Visual Search Task

A classical visual search task was displayed on a 19" computer monitor (Figure 8). The task was a timed, two-alternative, forced choice task where the target was either randomly present or not. The target was a red circle amongst a screen full of distracters (50 red squares and 50 blue circles) that share some but not all of the characteristics of the target. Each of the 50 screen shots were shown for up to 5 seconds each. If no choice was made within 5 seconds, the next screen was shown after a one second delay. If the subject made a determination that the target was either present or not before the 5 seconds had elapsed, the screen remained blank for the remainder of the 5 seconds plus a one second delay. This task continued for 5 minutes. This allowed for the measurement of reaction time, hits, false alarms, misses, and correct rejections. If desired, the interpretation of the results could employ a signal detection theoretic methodology. The visual search task was completed at the end of every odd hour (hours 1, 3, 5, 7) throughout the test session. Note the red circle in the lower left corner of Figure 8.

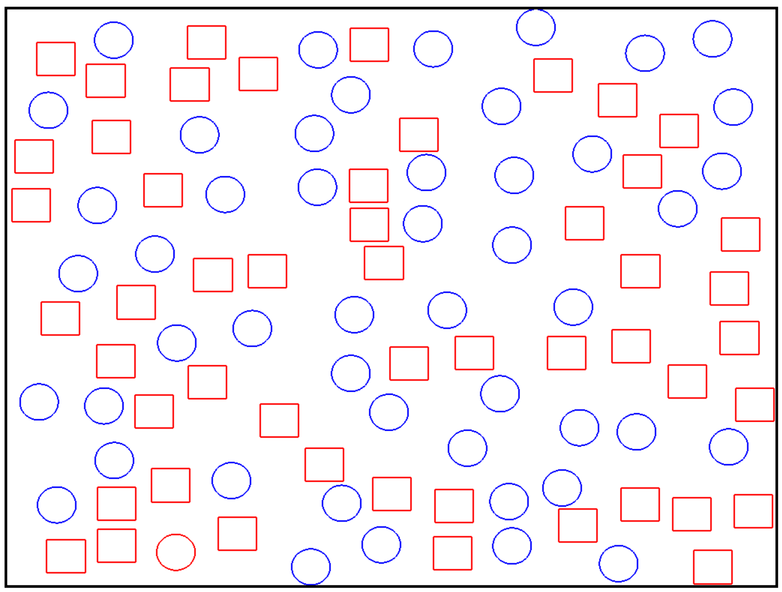

Figure 8. Example of Visual Search Task Screen

Awareness Check

Eleven targets were strategically placed around the test area to simulate "check-six" awareness checks. These targets consisted of large bold printed letters and numbers on 8.5 x 11 inch paper. Four targets were on the left, four targets were on the right, two targets were behind the subject (check-six location) and one target was in the front (Figure 9). Every fifteen minutes throughout the test session the test conductor would ask the subject to go through a routine of awareness checks lasting approximately 2 minutes. The subject would remain seated and turn only their head and neck toward the target (Figure 10). They would hold this position for 5 seconds and then move on to the next target as instructed by the test conductor. An additional minute was tacked-on to each awareness check occurring on the half hour. For this one minute, the subject would turn left and then right at a rapid pace at mirrored targets, or stare continuously at those

same targets for 30 seconds before switching. The order of the routines was predetermined and different for each awareness check, but was the same for each subject.

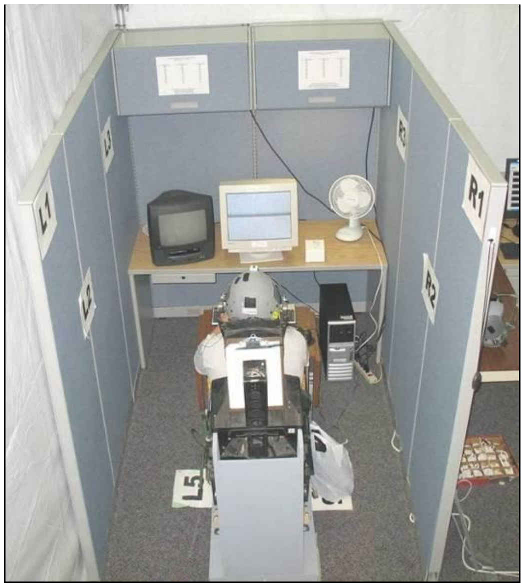

Figure 9. Placement of Awareness Check Targets (L1, R1, etc.)

Figure 10. Subject Performing Awareness Check

RESULTS

Twenty-five subjects (14 male, 11 female) participated in a total of 123 test sessions. Twenty-two subjects completed all five test sessions while the other three subjects completed only a portion of the tests due to scheduling conflicts or discomfort during testing. The subjects ranged in age (18-55 years), height (59.5-75.4 in.) and weight (115-301 lb.) as seen previously in Table 2.

Neck Strength and Endurance

The neck strength device was used to collect the subject's neck strength (100% MVC) at the beginning and end of each test session and the subject's neck endurance (70% MVC duration) every hour throughout the test session. The male subjects had significantly higher 100% MVC's than the female subjects (p=0.00012). The males' pre-test 100% MVCs ranged from 19.5 to 65.1 lbs. (mean = 34.0). The males' post-test 100% MVCs ranged from 20.5 to 68.6 lbs. (mean = 36.6). The females' pre-test 100% MVCs ranged from 14.0 to 53.3 lbs. (mean = 28.0). The females' post-test 100% MVCs ranged from 15.0 to 52.3 lbs. (mean = 27.9). Weak correlation was found between neck strength and subject's neck circumference at the mid-cervical spine, r = 0.477. No significant differences were found between the pre- and post-test strength pulls as demonstrated by the nearly identical 100% MVCs (Figure 11).

A t-test was performed on the neck stamina data which was measured by the subjects' ability to maintain their 70% MVC (Table 4, Figure 12). The male subjects had significantly longer endurance times than the female subjects for all helmet configurations except for the baseline helmet (3.0 lb.). No correlation was found when comparing neck stamina and neck circumference at mid-cervical spine (r = -0.032). Endurance times decreased throughout the 8-hour test session for all helmet configurations for males and females combined (Figure 13). The increase for the final hour for some of the test conditions was likely due to a motivational effect of finishing the day's session.

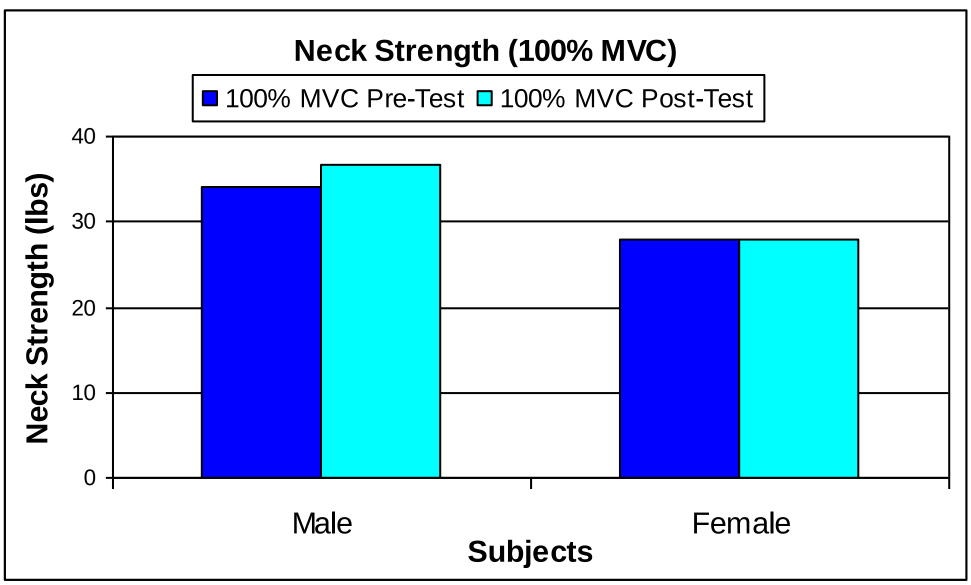

Figure 11. Mean MVCs for Male and Female Subjects

Table 4. Male and Female Mean Endurance Times

	Males (seconds)	Females (seconds)	p-value
A (baseline)	161	157	0.16181
B (4.5 lb, min CG)	164	157	0.00845
C (4.5 lb, forward CG)	154	146	0.00311
D (6.0 lb, min CG)	156	134	0.00002
E (6.0 lb, forward CG)	157	139	0.00085

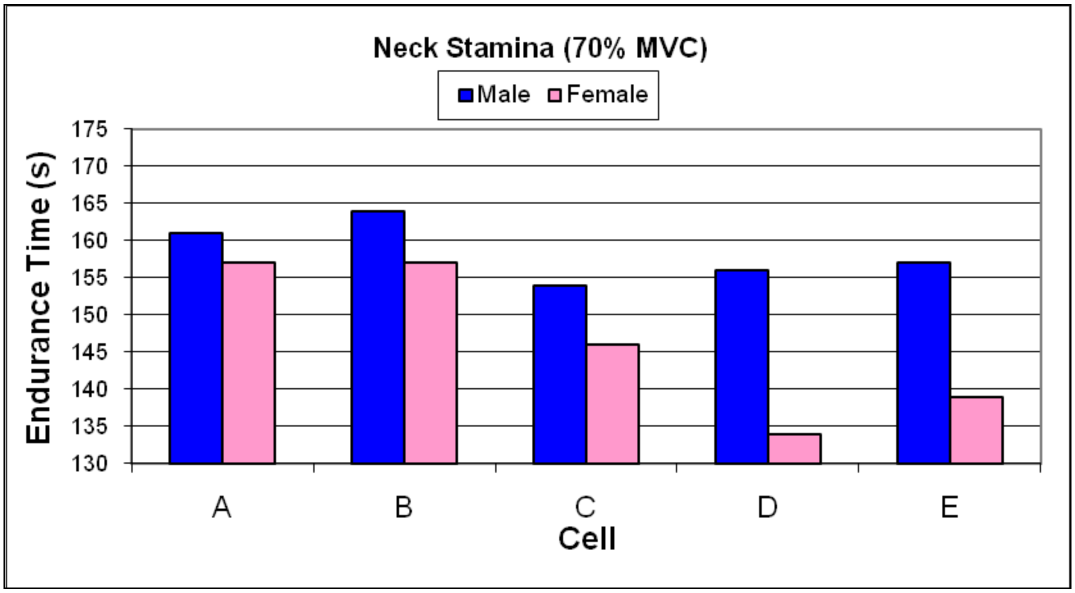

Figure 12. Male and Female Mean Endurance Times (s)

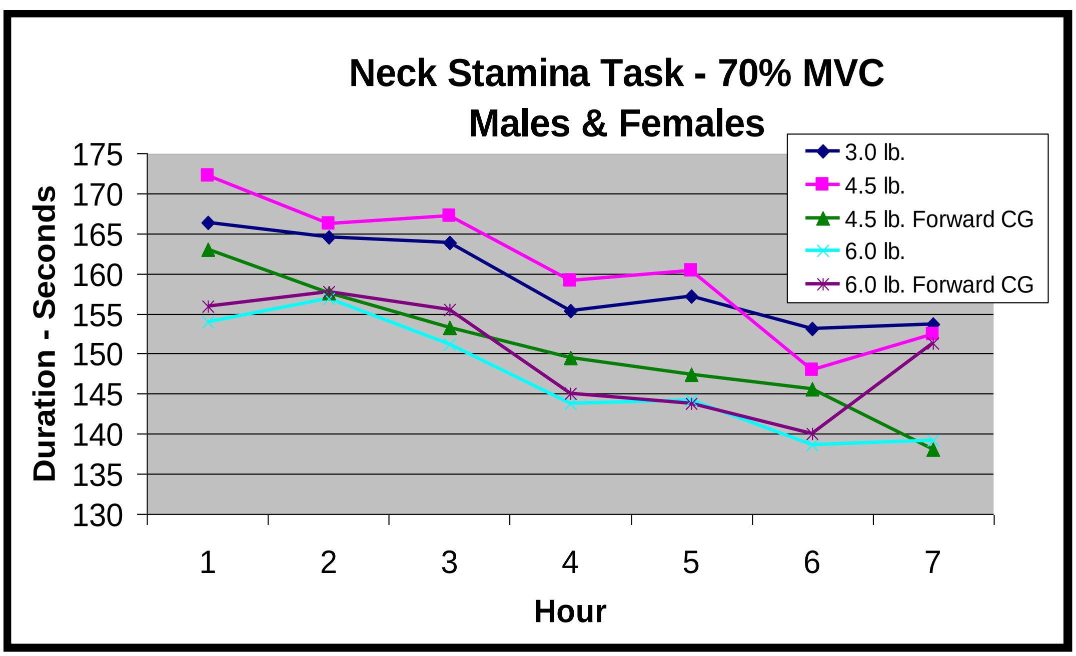

Figure 13. Group Endurance Times throughout All Sessions

EMG

Muscle fatigue was determined by measuring relative changes in the EMG root mean square (RMS) amplitudes and decreases in the EMG frequency content. Muscle fatigue is generally accompanied by increases in amplitude and shifts in the EMG spectrum to lower frequencies during prolonged contractions.

Very little muscle activity and fatigue was observed from the SCM and upper trapezius muscles. For neck extension, the SCM and upper trapezius muscles are not used nearly as much as the splenius capitus. Figure 14 displays raw EMG data taken from the right splenius capitus muscle during an endurance test. No significant muscle activity differences were found between helmet configurations. Amplitude RMS analysis on the SCs revealed higher levels of muscle fatigue during the final hours of the test session versus the beginning hours (Figure 15). Figure 16 displays the amplitude report: calculated amplitude RMS line plots for all 6 muscles (on the left side of the figure) and a column plot of the mean amplitude RMS per muscle (on right side of the figure). The amplitude report is automatically generated by the DelSys EMG Works Analysis 3.5 Program. This report confirms the SC muscles had higher activity levels than the SCM and upper trapezius muscles. Figure 17 was taken from the Right SC of a subject during an endurance test; this graph displays the MDF data. No changes indicative of fatigue in median frequency (MDF) were measured (Figure 18).

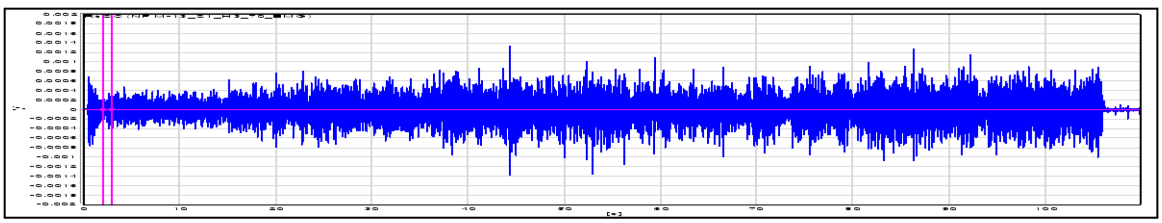

Figure 14. Sample raw EMG data from endurance test - Right Splenius Capitus Muscle

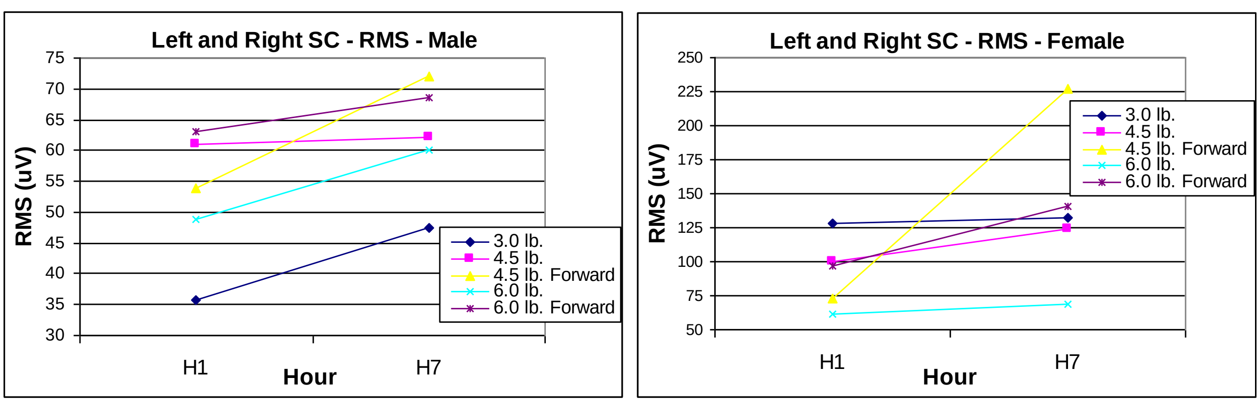

Figure 15. Mean RMS of the SCs throughout the Session: Males (*left*), Females (*right*)

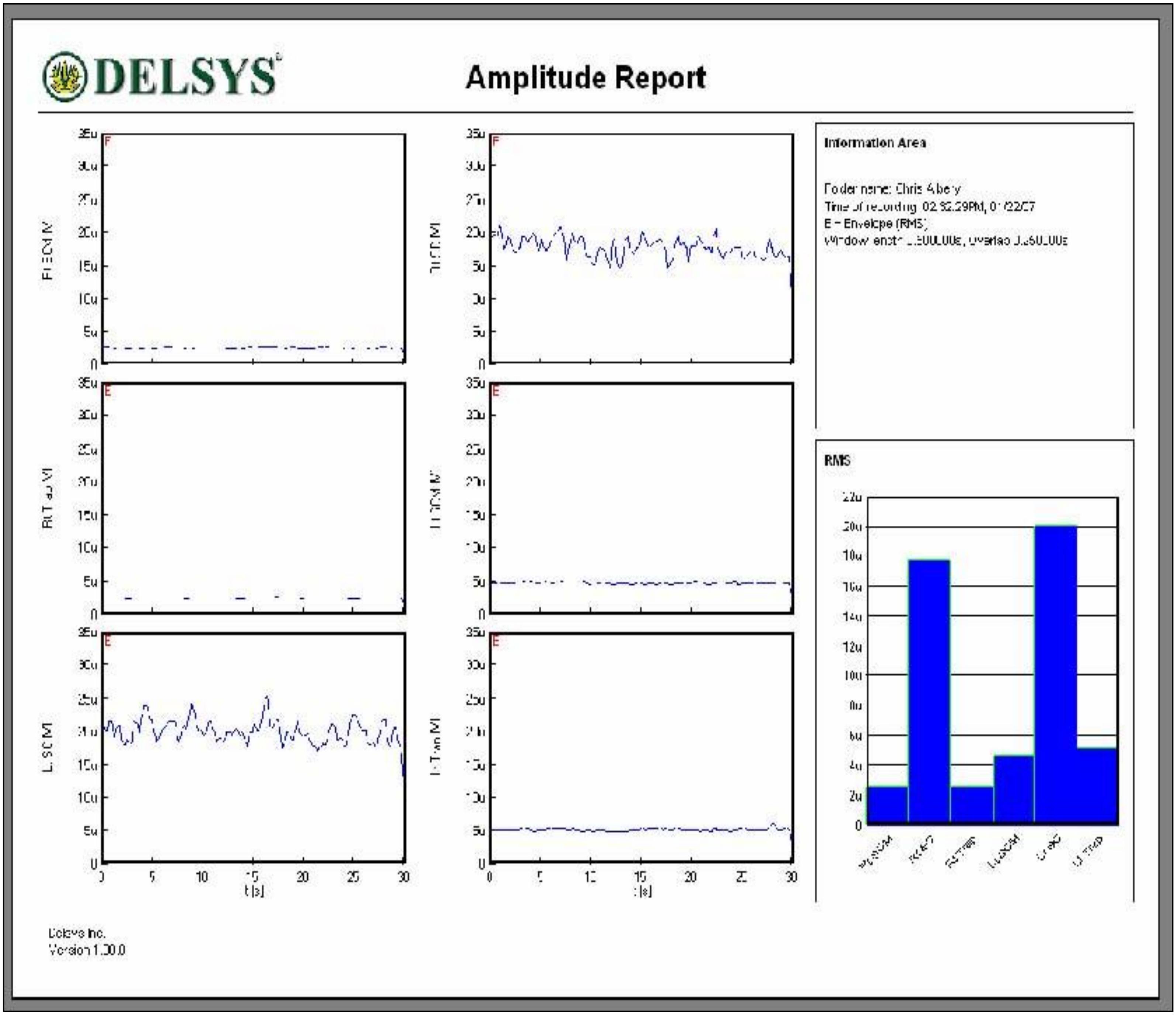

Figure 16. Amplitude Report for All Muscles

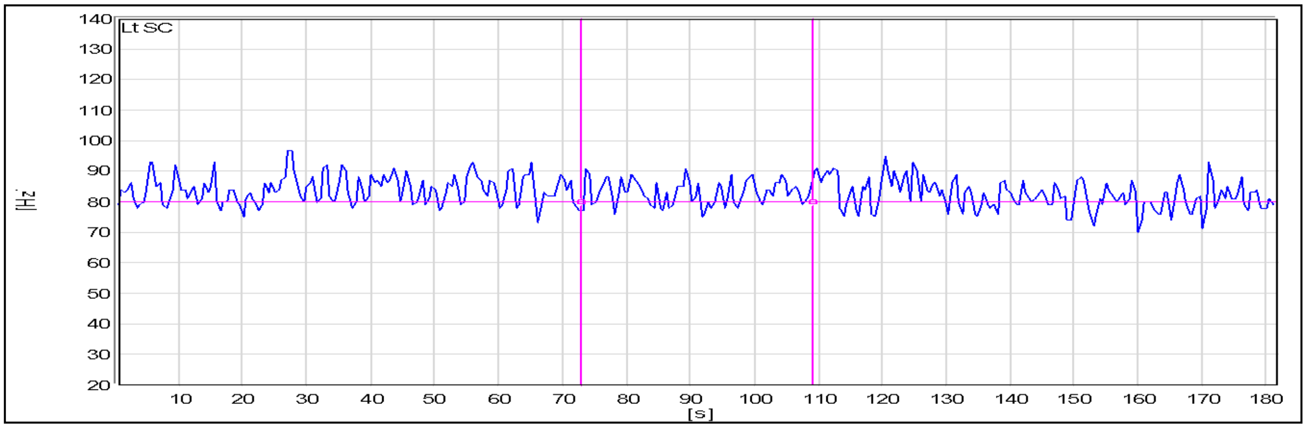

Figure 17. Sample of Right SC MDF Data from Endurance Run

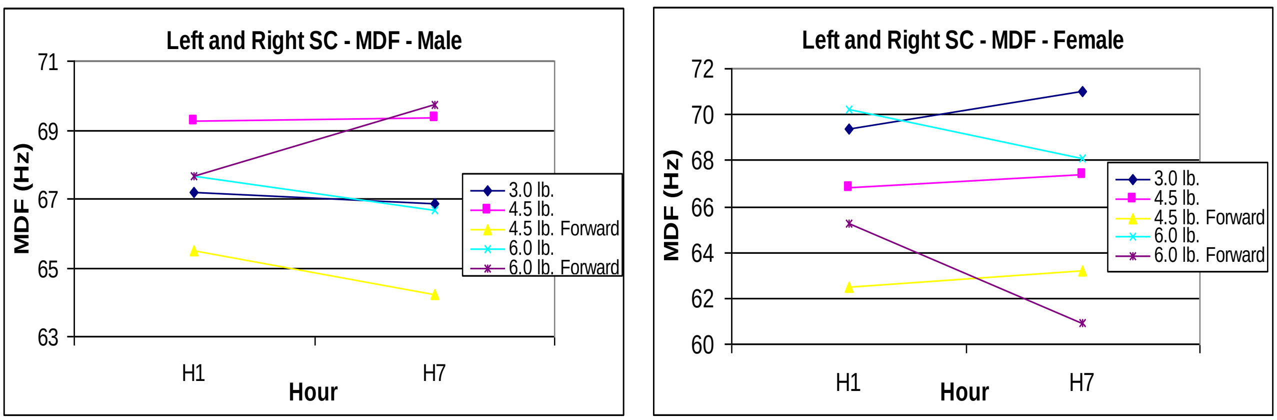

Figure 18. Mean MDF of the Right and Left SCs throughout the Session: Males (left), Females (right)

Subjective Comfort Survey

The comfort survey was given to the subjects pre- and post-test, as well as every other hour throughout the session; a total of seven surveys were completed per session. Repeated measures ANOVA tests were performed as a group to compare the subjects' reported discomfort associated with a change in helmet CG (nominal vs. forward), a change in weight (3.0, 4.5, 6.0 lbs.), and the 4.5 lb. forward CG helmet compared to the 6.0 lb. nominal CG helmet. Comparisons were made between hour 0 and all the proceeding hours that the comfort survey was taken (hour 2, 4, 6, and 7) to determine significant increases in subject discomfort levels and at what hour the significant increases were reported, $\alpha = 0.05$ (Table 5). Observations are summarized below.

- Significant levels of neck and back discomfort were reported for the 4.5 and 6.0 lb. helmets with a forward CG shift when compared to the 4.5 and 6.0 lb. helmets with a nominal CG shift (Figure 19).
    - Significant increases in upper neck and upper and lower back discomfort were reported from hour 0 to hours 2 and 4.

  - Significant increases in upper and lower neck and upper and lower back discomfort were reported from hour 0 to hours 6 and 7.
- When considering only the change in helmet weight (not CG), significant increases in lower back discomfort were reported from hour 0 to hour 4
- No significant gender differences were found when comparing the subjects' reported discomfort associated with a change in helmet CG and/or a change in helmet weight.
- Significant levels of neck and back discomfort were reported for the 4.5 lb. helmets with a forward CG (Cell C) shift when compared to the 6.0 lb. helmets with nominal CG shift (Cell D) (Figure 20).
  - Significant increases in upper neck discomfort were reported from hour 0 to hours 2, 4, 6, and 7.
  - Significant increases in lower neck and upper back discomfort were reported from hour 0 to hours 6 and 7.
  - Significant gender differences were reported from hour 0 to hour 6 for the upper neck ($p=0.045$) and lower back ($p=0.035$) where females reported higher levels of discomfort.

Notably, nearly all subjects verbally reported preferring a heavier, balanced helmet over a lighter, unbalanced helmet. The most common verbally reported complaints were headache, sore neck and upper back muscles.

Table 5. P-Values from the Comfort Survey

	Change in CG (Nominal, Forward)	Change in Weight (3.0 lb, 4.5 lb, 6.0 lb)	4.5 lb Forward CG vs. 6.0 lb Nominal CG
H0 – H2			
Upper Neck	0.000	0.249	0.001
Lower Neck	0.310	0.521	0.945
Upper Back	0.042	0.876	0.212
Lower Back	0.042	0.328	0.494
H0 – H4			
Upper Neck	0.000	0.777	0.003
Lower Neck	0.083	0.210	0.765
Upper Back	0.013	0.873	0.165
Lower Back	0.043	0.021	0.563
H0 – H6			
Upper Neck	0.000	0.582	0.000
Lower Neck	0.003	0.149	0.024
Upper Back	0.026	0.769	0.025
Lower Back	0.012	0.155	0.316
H0 – H7			
Upper Neck	0.000	0.493	0.000
Lower Neck	0.009	0.349	0.038
Upper Back	0.012	0.269	0.017
Lower Back	0.020	0.094	0.549

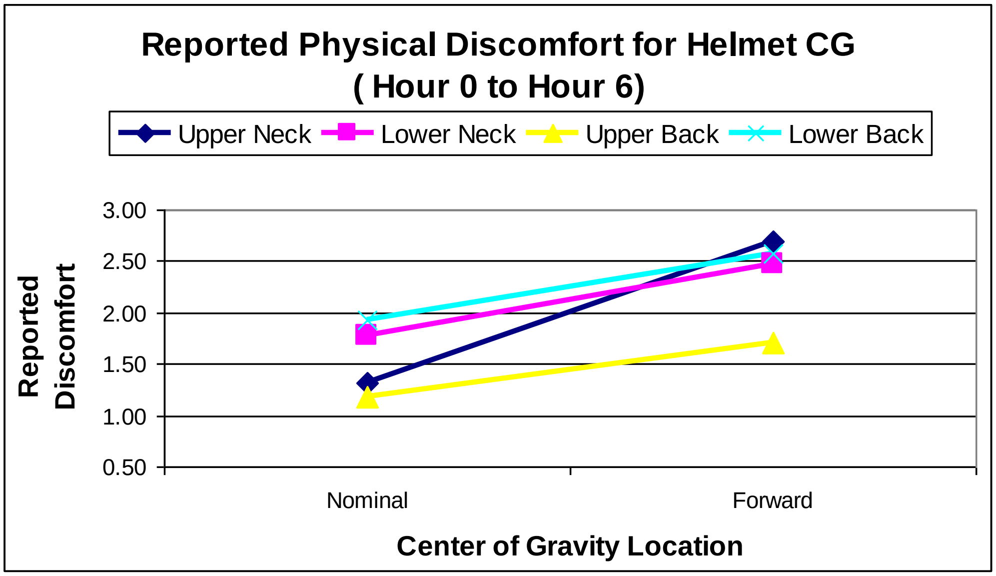

Figure 19. Neck and Back Discomfort: Forward CG Helmets vs. Nominal CG Helmets

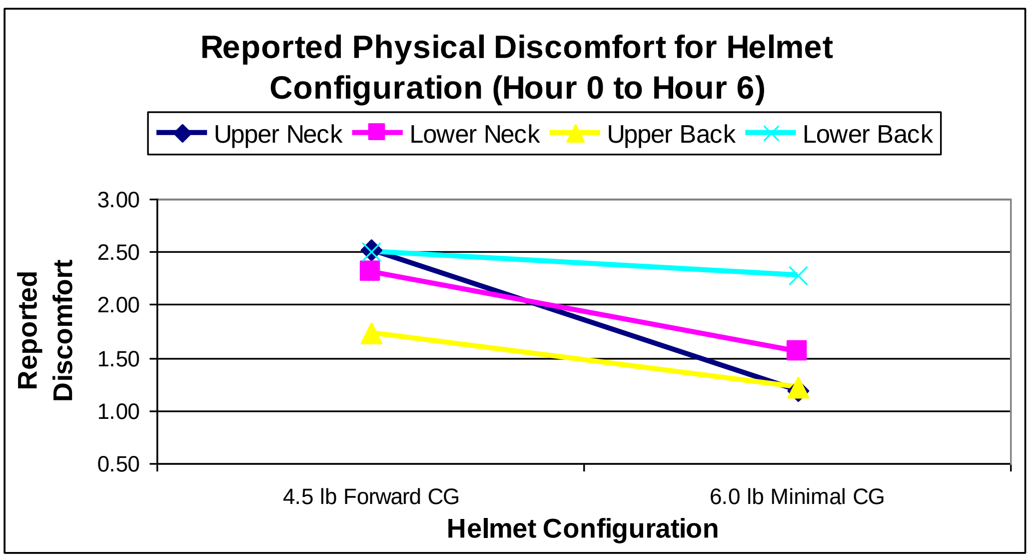

Figure 20. Neck and Back Discomfort: 4.5 lb. Forward CG Helmets vs. 6.0 lb Nominal CG Helmets

Visual Search Task

Each subject completed the visual search task displayed on a 19 in. color monitor at the end of hours 1, 3, 5, and 7 (four times per test session). A repeated measures ANOVA test was performed with helmet configuration and time as within-subject factors, and gender as a between-subject factor. Four measures were analyzed including:

- correct target detections
- timeouts
- false alarms
- search time for correct target detections

Correct target detections were computed from the number of times a subject correctly detected the presence of a target, excluding from the denominator those trials on which a subject failed to make a response before the 5-second time limit. Subjects averaged 88% correct responses across all conditions. There were no significant main effects or interactions. Timeouts were defined as the percentage of trials that a participant failed to make a response within the 5-seconds. In general, subjects made very few timeouts, and of these, most occurred when a target was not present, suggesting that they simply continued searching as time ran out. The timeouts occurred on only about 1% of the trials on which a target was present. The analysis suggested that this measure was not affected by any of the experimental conditions (i.e. helmet configuration, hour taken, etc.).

False alarms were calculated when the subject responded that a target was present even though there was no target. The percentage of false alarms was very low (≈ 1%) and did not differ as a function of any of the independent variables. Search time for correct target detections was defined as the amount of time it took to detect the target. This measure is the most indicative of search difficulty. This was the only measure for which the statistical analysis revealed any effect, and this was a main effect for time. Specifically, the time it took to accomplish the search decreased throughout the session as the subject became more familiar and better at the task (Figure 21). The average search time was about 2200 ms.

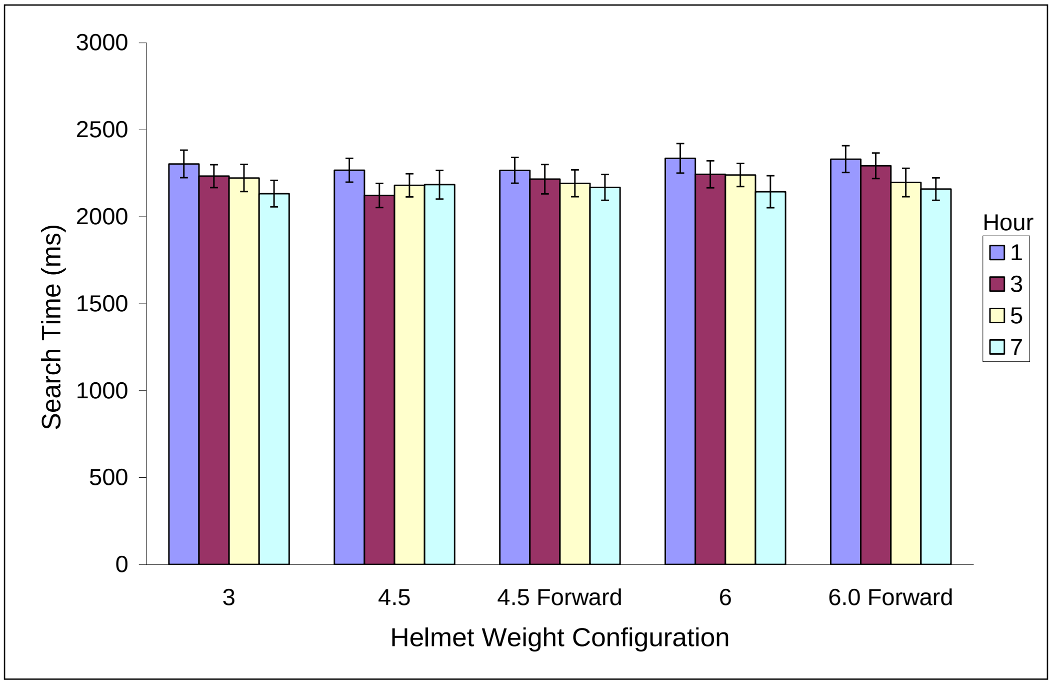

Figure 21. Search Time for Target, Helmet Configuration, and Hour Performed

DISCUSSION

The neck strength device provided a method to measure subjects' neck strength and endurance. As hypothesized, the males had significantly greater neck strength and endurance times than the females. However, no significant differences were found when comparing subjects' post-test 100% MVC to their pre-test 100% MVC, indicating neither the helmet nor duration that the helmet was worn affected the subjects' maximum neck strength. The use of a lap belt may have helped the subjects' buttocks from sliding/slipping on the device's chair as they performed their strength and endurance runs and may have resulted in larger MVCs. Most subjects were able to hold their 70% MVCs for the full three minutes, whereas previous studies had found that subjects exerting a 70% MVC had an average endurance time of only 50 ± 7 seconds[25]. With a larger 100% MVC, the calculated 70% MVC may have been harder for the subject to hold within the 70% ± 2 lb. envelope resulting in shorter endurance times and greater cumulative fatigue on the neck. Likewise, this may have resulted in a neck strength difference between the post-test and pre-test MVCs.

The neck endurance results showed no significant decrease in endurance times for all helmet configurations. An increase in endurance times was found for all helmet configurations from hour six to hour seven except for the 4.5 lb. helmet with the forward CG. The subjects often appeared more motivated for the post-test MVC knowing their 8-hour session was almost over. The males had significantly longer endurance times than the females for all helmets except the 3.0 lb. baseline helmet configuration.

The surface EMG results indicated that very little muscle activity was recorded for two of the three sets of muscles. Only the splenius capitus (SC) muscles provided meaningful data during the neck strength and endurance tests due to the rearward pulling (extension) motion of the neck. An increase in the amplitude was found after analyzing the SC data RMS while no changes in frequency MDF were noted. The lower trapezius, mid back, and lower back muscles may have shown some interesting activity based on subject's verbal comments, but were not monitored for this study.

The comfort survey was given throughout each test session. Subjects' comfort levels decreased significantly throughout the test sessions. A significant increase in neck and back discomfort was reported beginning at hour 2 and continuing throughout the test session for helmets with a forward CG shift when compared to helmets with a nominal CG shift. Most subjects complained about wearing any of the helmets for the entire test session. Subjects reported how uncomfortable it was to wear either of the forward CG shift helmets. Subjects reported the 6.0 lb. forward CG shift helmet was the most uncomfortable. While wearing the forward CG helmets, subjects were often asked to stop supporting the helmet and/or their chin with their hands. Subjects reported significantly greater neck and back discomfort while wearing the 4.5 lb. forward CG shift helmets as compared to the heavier 6.0 lb. helmet with a nominal CG shift. An increase in helmet weight did not correlate with an increase in subject discomfort.

The visual search task served as a performance measure. This task, regardless of helmet configuration, did not result in any significant difference when analyzing correct target detection, timeouts, false alarms, or search time for correct target detection. False alarms were looked at more closely because sometimes under workload, deterioration in subject performance is due not so much to missed signals as to increased false alarms. However, this proved not to be the case. Subjects were able to easily complete the search task; in fact, the results showed an increase in performance throughout the test session which was most likely due to a training effect. This task proved to be too easy. An increase in the size of the screen would require the subject to move their head and neck more, and might affect their performance based on head/neck supported weight and wear duration. Another way to make the task more demanding would be to decrease the available search time, and/or increase the number of targets. A realistic flight simulation task performed on a large screen may also prove beneficial.

CONCLUSIONS

Overall, subjects were able to complete the five test sessions, regardless of helmet configuration. Males had significantly stronger MVCs and longer endurance times than females. Helmets with a forward CG were significantly more uncomfortable on the subjects' neck and back than the helmets with a nominal CG shift. Significant increases in upper neck and upper and lower back discomfort were reported as early as hour 2 and continued throughout the session. The 4.5 lb. helmet with forward CG was significantly more uncomfortable on the subjects' neck and back than the 6.0 lb. helmet with the nominal CG shift. Again, significant increases in upper neck discomfort were reported as early as hour 2 and continued throughout the session. In general, no significant gender differences were found for comfort. Surface EMG amplitude analyses indicated higher levels of fatigue for the final hours as compared to the beginning hours of each session regardless of helmet

These results support the importance of keeping the helmet system as light and balanced as possible. More specifically, these data support the Air Force Research Laboratory's recommendation that helmet systems be kept at or under 5 lbs. and should not shift the head/helmet system CG more than that recommended in Knox et al.[18]. This applies to special operations forces (SOF), mobility air forces (MOF), and combat air forces (CAF). Helmets weighing more than 5 lbs. or shifting the CG forward of the recommended limit will be a major concern for flights longer than a couple hours, and may lead to acute and/or chronic neck and back pain.

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